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Harmonic Generation of Ion Waves due to Brillouin Backscattering

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We report results of simulations of stimulated Brillouin backscatter in which we see the second spatial harmonic of the ion density fluctuation and compare with linear, fluid theory. We also describe examples of the competition between Raman and Brillouin backscatter.

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Introduction

We begin with a brief review of Raman and Brillouin backscattering, then describe the simulation results. Stimulated Raman scattering(SRS)[1-13] is the parametric decay of an incident photon into a scattered photon plus a longtitudinal electron plasma wave. The wave numbers, k, and frequencies, ω, obey the matching conditions characteristic of parametric processes:

$$k_0=\pm k_s+k_{epw} \tag{1}$$

$$\text{and } \omega_0=\omega_s+\omega_{epw}, \tag{2}$$

(the subscripts 0,s, and epw refer to the pump, scattered, and electron plasma wave, respectively and the - of ± refers to backscatter). As the electron plasma wave Landau damps and breaks, it heats electrons into a quasi- Maxwellian distribution of temperature[1] $T_{hot} \sim (m_e/2)(\omega_{epw}/k_{epw})^2$ in the absence of Brillouin scattering. Stimulated Brillouin backscatter (SBS) is a very similar phenomenon with the electron plasma wave (epw) being replaced with an ion acoustic wave (ia) in Equations 1 and 2.

Simulations

Fig.1 shows the k spectrum of the electron density vs time from a 1.5 dimensional (two velocities), electromagnetic, relativistic simulation (Oremp). The laser light with $I\lambda_0^2$=2.5x10^{15}W/cm^2 was propagated through a 128λ_0 slab of plasma with T_e=1kev, T_e/T_i=30, and n/n_c=0.05. Here I is the laser intensity, λ_0 is the laser wavelength, T_e is the electron temperature, T_i is the ion temperature, n is the electron density and n_c is the critical density where the plasma frequency equals the laser frequency. The brief line at kc/ω_0~1.7 represents Raman backscattering which occurs strongly only before the Brillouin scattering becomes large. We also measure the Raman backscattered light which was 0.04 of the incident intensity between times 114 and 370 laser cycles, and continued weakly at a reflection of 0.004 ($\omega_s/\omega_0 \sim 0.73$) between times 489–1001 even though the k spectrum is buried in the noise. This dramatic effect has been seen experimentally by Walsh, Villeneuve and Baldis[14]. The electron and ion density fluctuation at $kc/\omega_0 \sim 1.95$ is due to Brillouin backscattering and is most strong between times 300 and 600 cycles. At times 340–500, the second k harmonic of this density fluctution can be seen at $kc/\omega_0 \sim 3.9$ (shown also in Fig.2).

The theory presented here for second harmonic generation is outlined in Ref.15 (see also refs.16,17). Harmonic generation is another effect which acts to limit the ion wave amplitude, provided the wave number times the electron Debye length ($k\lambda_D$) is small. If we neglect $k\lambda_D$ effects, the frequency of an ion sound wave is simply proportional to its wave number. Such a wave will then steepen, since harmonics are resonantly driven. If we consider an ion sound wave with amplitude δn, wave number k, and compute the growth of its second harmonic by linearizing the two-fluid equations, we obtain

$$\delta n(2k)/n_p = (1/2)[\delta n(k)/n_p]^2/[1/(1+k^2\lambda_D^2) - 1/(1+4k^2\lambda_D^2)] \quad (3)$$

$$\approx (1/6)[\delta n(k)/n_p]^2/k^2\lambda_D^2, \quad (k^2\lambda_D^2 << 1) \quad (4)$$

Substituting the measured $\delta n(k)$ from Fig.2, and $k\lambda_D \sim 0.39$ into Eq.3 gives $\delta n(2k)/n_c \sim 0.0015$ in reasonable agreement with the simulated 0.002 in Fig.2. For $\delta n(k)/n_p >> 6k^2\lambda_D^2$ (found from Eq.4 with $\delta n(k) \sim \delta n(2k)$) the above linearization is invalid, and a rich spectrum of harmonics is expected (to be discussed in a future publication). Spatial harmonics of Brillouin-generated ion fluctuations have also been observed by Walsh and Baldis[18] at NRC(Canada) and by Luhmann and Pawley at UCLA[19].

In an identical simulation with the ions fixed, the k spectrum has a pulsating character as noted before[3] with a peak fraction absorbed of ~0.04 and a long time fraction of light reflected = 0.016 within times 481-993 cycles. The average x energy increases from 0.5 to 0.9 kev by 600 laser cycles (x is the direction of the electrostatic field and the laser propagation).

Examples of the competition between Brillouin and Raman.

We have previously reported simulations[3,13] which show that Brillouin scattering can reduce Raman absorption and that Raman heating can reduce Brillouin scattering and raising T_e and reducing Brillouin gain. Table I outlines the results of several runs:

Table I

n/n_c	T_e	T_e/T_i	Raman backscattering	T_{hot}
0.05	1	30	.04,.004	4.5
0.05	1	fixed	.04,.016	6
0.1	1	3	.18	12
0.1	1	30	.12	10
0.1	1	fixed	.26	17
0.2	3	5	.33	50
0.2	3	fixed	.33	60

The second number in the backscatter column represents the long term (time greater than 500 cycles) Raman reflection.

Two effects that may explain the decrease in Raman scattering are (1) pump depletion by Brillouin scattering and (2) competition from the shorter wavelength Brillouin fluctuations. In the n/n_c=0.05 case there was time averaged 22% Brillouin scatter and about 2.3 e foldings reduction in Raman gain. Since the Raman backscattering $\propto$ exp(the Raman gain) $\propto$ exp(the available $I\lambda_0^2$), one can see how a 22% reduction in pump intensity could make an order of magnitude difference in the scattering providing the damping remained constant. Of course, the damping does not remain constant, which is where the second effect comes in; that is the damping[20,21] due to the shorter wavelength ion waves. Rozmus, Offenberger, and Fedosejevs[20] describe a Raman threshold in terms of the ion turbulence.

We have also noted[3] that the Brillouin instability can decrease the heated electron temperature of Raman backscatter. Two possible explanations are that the Raman instability can occur at the k of the Brillouin ion wave or that the Raman plasma wave is coupled to a shorter wavelength at $k=k_{epw}+k_{brill}$. Neither of these hypotheses are entirely explored; however, we have some preliminary results. We solved the Drake and Lee equation for the growth rate of Raman backscatter (Fig.3) and find that the growth rate at the k of the Brillouin instability is down several decades. Not shown here are also solutions using the T_{cold} and T_{hot} distribution functions found in the simulation which do not show enough growth at the k of the Brillouin ion fluctuation. Conceivably, there is still some coupling to the Brillouin k as evidenced by the T_{hot} being well represented by $(m_e/2)(\omega_{epw}/k_{brill})^2$; however, this is by no means proof. We also measured the scattered light peak for Raman with moving and fixed ions and found that the peak was essentially unaltered showing ω_{epw} was almost the same. It there is an electron plasma wave occurring at $k=k_{epw}+k_{brill}$ due to coupling on the Brillouin it wave, it can not be resolved from the noise in Fig.1.

In conclusion, we have simulated the second harmonic generation of ion waves due to Brillouin backscattering and have compared that favorably with theory. We have presented simulation evidence that

T_{hot} and absorption due to the Raman instability are reduced in the presence of the Brillouin instability.

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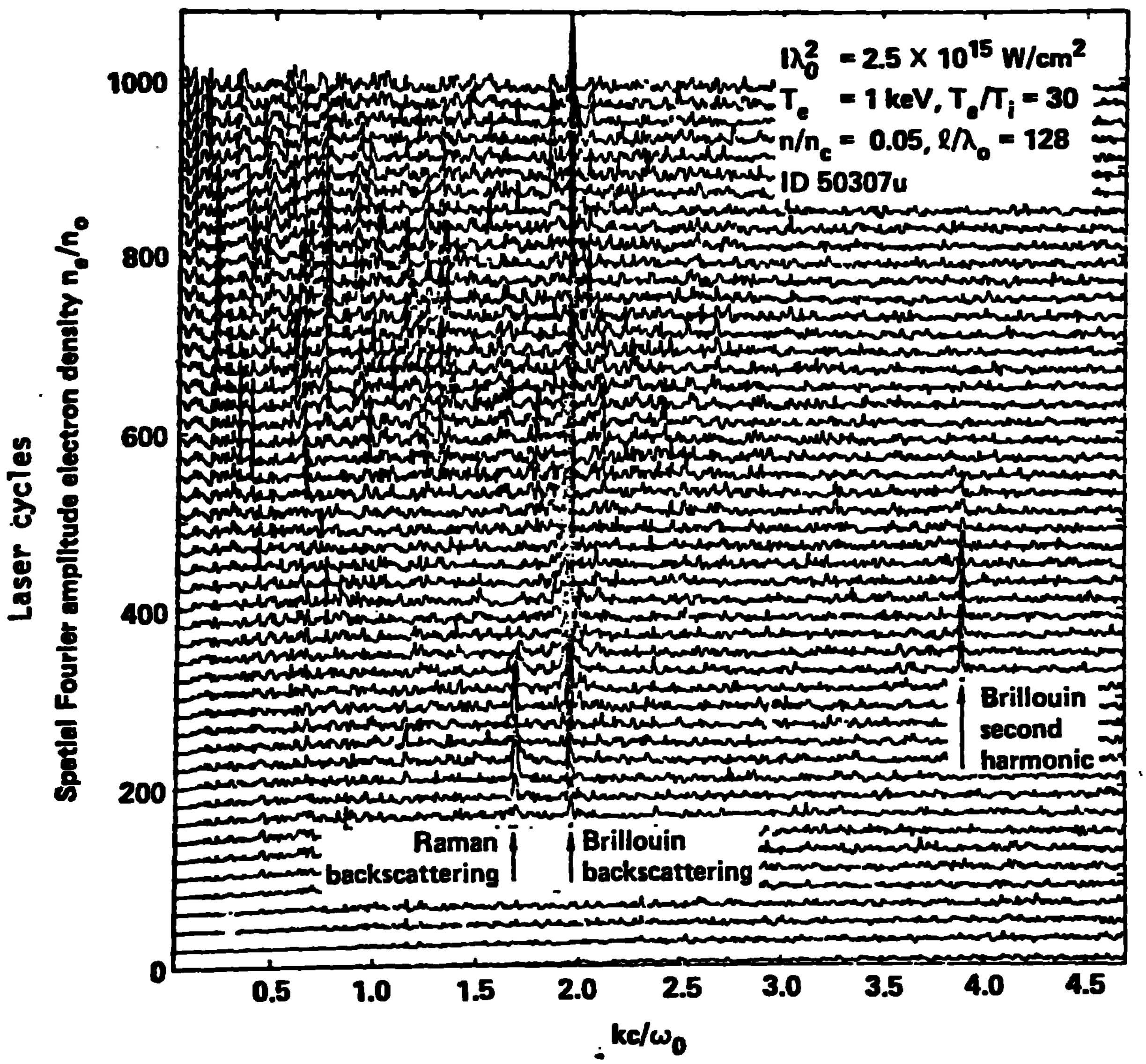

Fig.1. Wave number spectrum of the electron density vs time(up) and kc/ω_0 (across). and n/n_c. The laser intensity $I\lambda_0^2=2.5\times10^{15}$ $W\cdot\mu m^2/cm^2$, T_e=1 keV, T_e/T_i=30, n/n_c=0.05 initially constant for $128\lambda_0$.

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Fig. 1

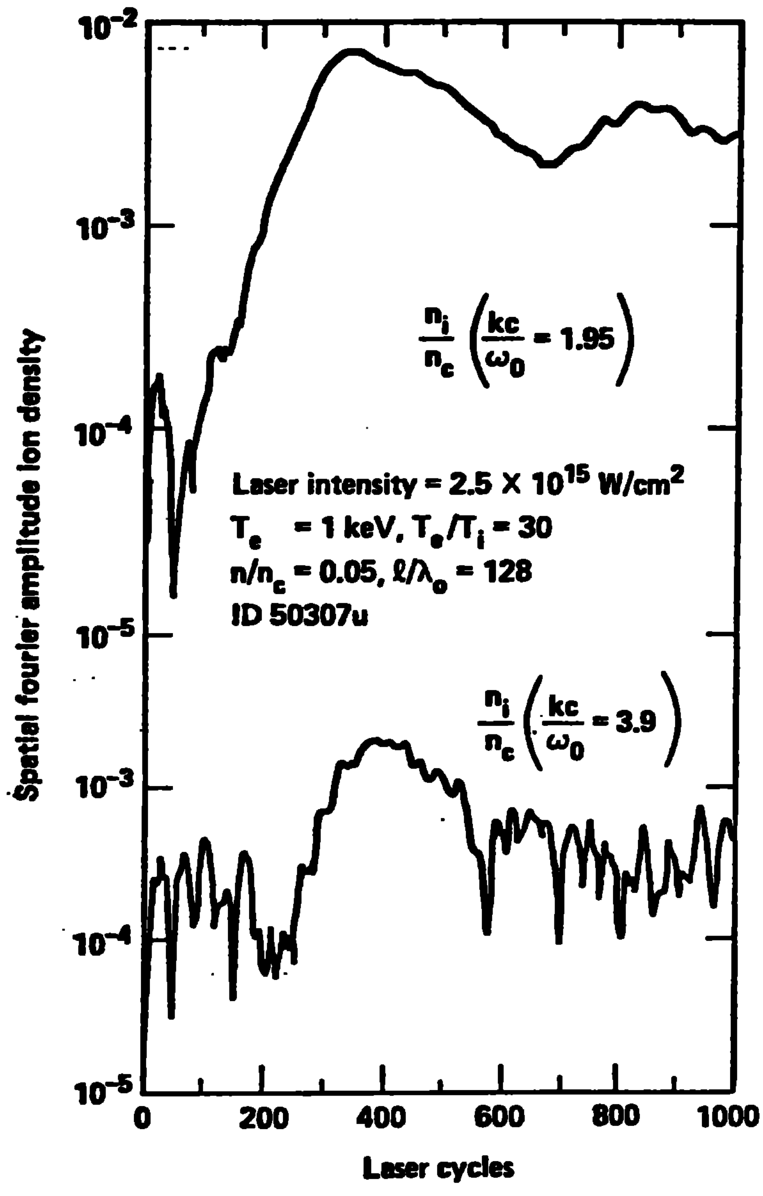

Fig.2. Spectral amplitude of the Brillouin fundamental and second harmonic vs time.

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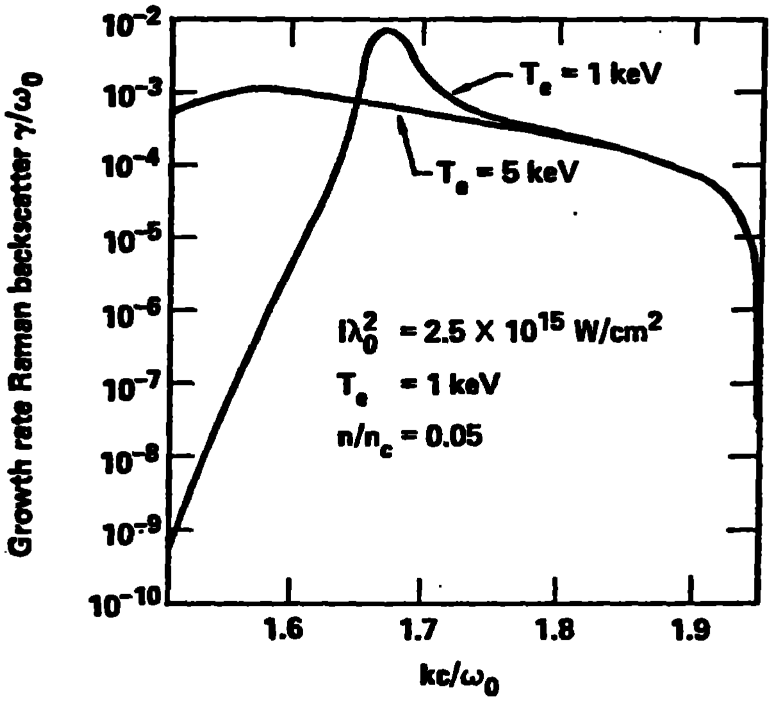

Fig.3. Growth rate of Raman backscatter vs $k_{epw}c/\omega_0$.

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Fig.3